Available online at www.sciencedirect.com

ScienceDirect

Procedia Technology 15 (2014) 398 – 405

Procedia Technology

2nd International Conference on System-Integrated Intelligence: Challenges for Product and Production Engineering

Flexible, self-configuring control system for a modular production system

Stefan Scheifele, Jens Friedrich*, Armin Lechler, Alexander Verl

Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW), University of Stuttgart, Seidenstr. 36, 70174 Stuttgart, Germany

Abstract

This paper presents a control concept of a modular manufacturing system (MPS). Having exchangeable process modules, the system can produce a wide range of products. For process modules a new concept for a Configuration and Information Memory (CIMory) is proposed. The CIMory provides a description of the module and its capabilities. Based on this information the control system, as well as the guidance system configures itself. The control follows a holistic approach with a hybrid structure to support both, modules with internal intelligence or with a simple command executing I/O unit. A Workflow Manager (WFM) organizes the production processes and the data exchange between all modules and the human-machine interface (HMI).

Peer-review under responsibility of the Organizing Committee of ICIAME 2014.

Keywords: Modular Production System (MPS); Configuration and Information Memory (CIMory); Workflow Manager (WFM); self-configuration

1. Introduction

Today´s production needs are rapidly changing. To cope with increased need of customized products [1, 2] and the shorter product lifecycles, production systems needs to be flexible and reconfigurable. This approach is seen as the best method to implement different functional requirements with a minimum amount of resources [3], as well as

* Corresponding author. Tel.: +49-*0711 685-82416*; fax: +49-*0711 685-72416*.
E-mail address: Jens.Friedrich@isw.uni-stuttgart.de

Peer-review under responsibility of the Organizing Committee of ICIAME 2014.
doi:10.1016/j.protcy.2014.09.094

the possibility to optimize the operational capacity of the whole system by adding modules to the slowest production step [4]. Due to the interconnection of the machines, new and adaptive value chains will develop [5]. Therefore production systems can be divided into standardized modules which can be exchanged to fulfill the requirements of the production process.

The development of standardized mechanical interfaces has improved the time consuming mechanical reconfiguration to such a high level that the reconfiguration of the control system becomes the bottleneck [6]. Mechatronic information models for modeling of automation components and machines have been defined [7], as well as rules for the creation of software development kits [8]. Based on this preliminary work, modern engineering companies with the help of software tools for engineering (e.g. EPLAN [9]) are able to generate machine configurations for individually configured machines from a central repository. However, this is a time and manpower consuming action and the vendor of the production system has to maintain the module set for the engineering tool software. Because of no common standard for the required configuration, it is a high effort to integrate new modules in the engineering system.

The availability of factory wide and world wide networks leads to a change of the production environment and the organization. The structure will be more decentralized and all components will be linked to each other [10]. The connections for data and information exchange can be changed during runtime [11]. This will increase the use of cyber physical systems (CPS). The use of CPSs provides added value for smart factories like optimized production of customized products and resource-efficient production [12]. But the spread of CPS in the production will also lead to a change in the organizational and hierarchical structure of the manufacturing process. The established automation pyramid, which defines the organization of a production system, will vanish and will be replaced by a network structure [8, 13]. Thus new control concepts are necessary to support the distributed architecture [11].

A distributed production system can be controlled using an agent-based control system [14, 15, 16]. The production will organize itself, each part “knows” its requirements and each machine “knows” its capabilities. There is no reconfiguration or change of the system necessary, if there are additional components in the system. The part finds all the necessary productions steps independently by negotiating with all participants in the system [15]. But this structure does not always lead to the optimal solution [17], it can even happen, that due to the independent behavior of all participants a dead lock occurs that blocks the complete multi-agent-system [18]. The functional, hierarchical structure of the control system can also be kept in a distributed and modular control system [19]. In a master-slave-configuration, one controller supervises the components and their controllers. If one component is changed a reconfiguration of the master-controller is necessary.

Modular Production Systems (MPS) have been suggested by Koren et al. [20, 21]. An adaption of the MPS to a special use case is mentioned, but only in predefined manner. For example, an adding of a module is only allowed to a predefined production step for adapting the MPS to speed up slow production steps by parallelization of work. Also the module to be added has to be predefined to the control system. An adding of a previous not defined module is only possible by re-configuring the control system of the MPS, which is done by time consuming work, like mentioned before in this paper.

One approach for modular production systems is presented by Järvenpää [22], in which a base module for production modules is defined with control cabinet and clean room supply systems, providing a predefined work space in a clean environment. Into each base module different production modules (e.g. robot, laser or machining unit) can be integrated, but only one at a time. By attaching these process integrated base modules next to each other, an entire production system can be established. Due to the modular structure of the concept and plug-and-play interfaces of the modules, it is easy to mechanically reconfigure the system to different product requirements. However, the automatic software reconfiguration is not taken into account.

Another similar approach by Hoffmeister et al. [23] focusing on small machine tools for small work pieces uses a predefined hardware frame for production modules to which kinematic or process modules can be attached. The modularity is reached by the frame and suitable hardware interfaces, but again, the automatic software reconfiguration, especially for the interconnection of multiple modules is not considered.

In this paper a new concept for a control system with a distributed architecture is described. It follows a hierarchical structure with a master control (Workflow Manager). The reconfiguration of the control is done automatically if a module is changed. There is no effort for the vendor of the production system to maintain the configuration information of all modules, because each module has a special memory (CIMory) containing all

necessary information. By using these standardized interfaces different manufactures can provide modules, which can be integrated into the production system.

Within the CassaMobile project [24], a mobile, flexible, modular, small-footprint manufacturing system in an ISO-container that can be easily configured for different products and processes is developed. The container based manufacturing system can be easily configured for different products and manufacturing processes. As shown in Fig. 1 it is also possible to integrate several modules of the same type into one production system to optimize the productivity, if e.g., one process is slower than the other.

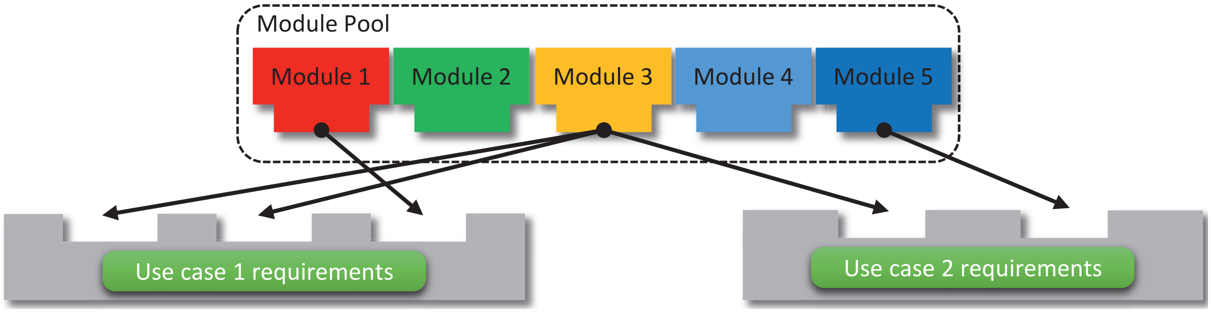

Fig. 1. Concept of the Modular Production System (MPS) combining modules to fit the use case requirements.

2. Overall system architecture

The new system architecture is shown as a schematic diagram in Fig. 2. The production system is split into discretized modules which are connected via a communication system which allows a service-oriented architecture (SOA) based communication for production requests, according to the reference model of OASIS [25], and a real-time (RT) based communication for hardware controlling tasks. The central module of the new system architecture is the Workflow Manager (WFM) which presents the production system to the higher level systems (e.g., an ERP System) and receives the product requirements supplied by the operator to the human-machine interface (HMI).

The production capabilities of the MPS are defined by the installed modules. Every module contributes one or more production capabilities e.g., 3-axis milling, 5-axis milling, part handling, cleaning and sterilization or additive manufacturing. The WFM handles the distribution of the production tasks based on the capability of the modules and implements a work and production flow spanning one or multiple modules which leads to the final product.

In general, a module consists of a mechanic and kinematic structure, the inputs and outputs (I/O) for the sensors and actuators, as well as drive amplifiers (Drives). To configure such modules, the WFM reads each module's CIMory while communicating during configuration. The WFM itself has a Configuration Manager (Config Manager), which handles the configuration to set up every module's needed SOA service list.

Concerning the control system, there are two types of modules: The first type of module has a built in control system, which is completely configured on delivery. This type is used for modules that require a high performance control system. The second type of modules are using a central control system. If, however, a module does not have its own integrated control system, the CIMory provides such information to the Config Manager, which in turn uses the Central Control System (CCS) module to implement a separate, software-based real-time control system for that particular module. There are two motivations for not embedding a sophisticated control intelligence such as CNC or PLC into the modules itself: cost reduction of the single module or no necessity for a powerful control system, as the module has no production or no complex capability, such as handling.

Once the modules and CCS based control systems are in place, the SOA communication between the WFM and each control system is established. The needed information about all module offered services is again retrieved from every module's respective CIMory.

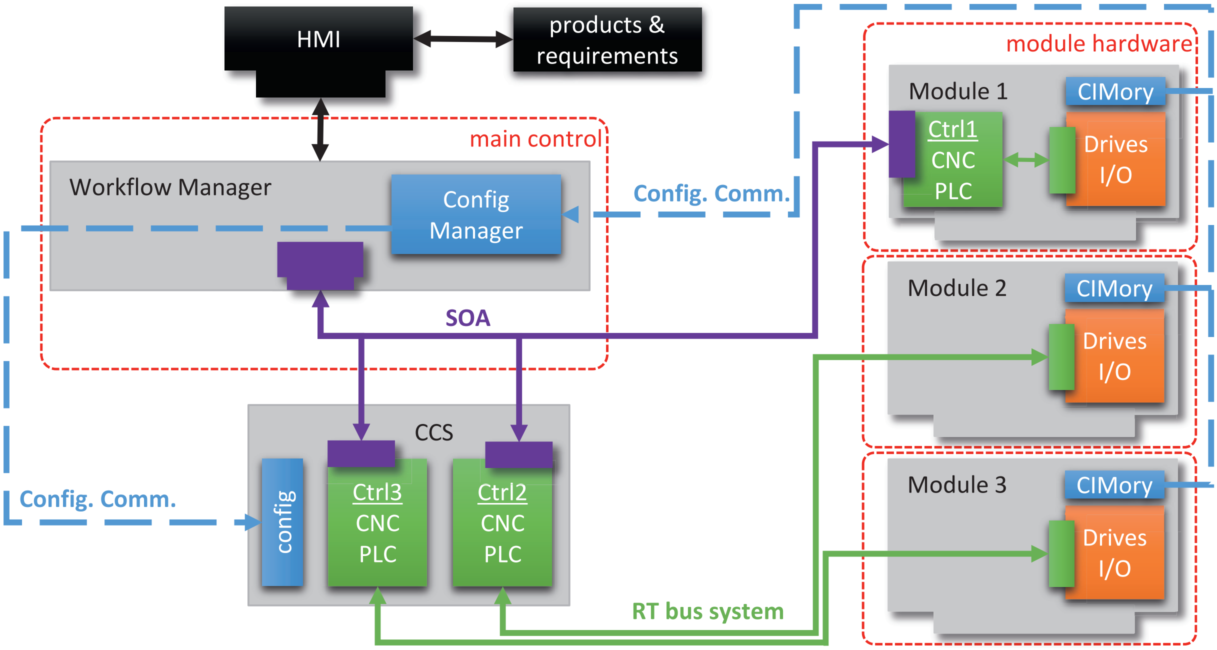

Fig. 2. Overall system layout with communication channels, module hardware, the Workflow Manager and CCS.

3. Self-configuration

Before starting the production program, the WFM checks the availability of all configured and required modules. Changes to the bus system or unavailable modules invalidate the active configuration of the WFM and initiate a bus scan for a reconfiguration process. Alternatively, a reconfiguration can be triggered manually by the user or upon the occurrence of bus errors caused by a communication error when removing modules from or adding modules to a running MPS.

The sequence of the self-configuration is given in the following:

1. The initial bus scan is triggered. The WFM detects all present CIMory in the bus system and reads the information regarding the module type and unique module ID.
2. The WFM Config Manager gradually accesses each detected CIMory and reads the stored module specific meta-configuration.
3. If a module has no own control system, the WFM Config Manager instantiates a RT-module control system to the CCS, based on the configuration data from the CIMory. This is followed by a validation of the configuration by the CCS.
4. The SOA communication is being established. Standard services offered are extended by the module-specific services defined by the CIMory.
5. The production system switches into run mode and the WFM charges the modules over the SOA services.

3.1. Purpose and description of the CIMory

In the MPS, there are two main parts that have to be reconfigured on module change: the WFM as well as the CCS. Production modules with their own control system are completely configured for immediate operation. A reconfiguration process does not contribute to the optimization of process behavior of a module and is therefore to be done only once at commissioning of the module.

The duty of the WFM is the distribution of production tasks to the modules based on their services offered and likewise their production capabilities. These must be announced to the WFM during the configuration step. Over the configuration communication the WFM receives the needed information and updates its SOA communication interface with the description of the needed data by the module, as well as the module and process specific form in which the data has to be delivered to the module. For example, a milling module needs the process describing data in form of G-Code, a cleaning module, however, needs simpler information like the cleaning time.

If a CCS is needed by at least one module, it also has to be configured with the needed configuration for the CNC and the PLC. All modules that require an external control system have a stored meta-configuration in the CIMory for configuring a control system instance to the CCS. The CCS is provided with the needed configuration data by the Config Manager of the WFM. For example, the control system on the CCS is in an abstract base configuration and, using the provided configuration for the CNC and PLC, is instantiated in module specific form. This means the base configuration provides the framework with module independent base functions which are expanded by the module specific configuration (see Fig. 3).

As described before, all module specific information needed for the self-configuration of the production system and the fast commissioning of a new constructed production system is located in the CIMory. The CIMory is a standardized memory, exclusively accessed by the Config Manager of the WFM over the configuration communication. The CIMory therefore consists of a multitude of specifically stored data. Firstly, the CIMory contains the module type ID that uniquely tells the WFM, what type of machine the module is. Additionally, it stores the module ID, a kind of serial number to uniquely address a module and thus allowing the MPS to use multiple identical production modules, for the same production process in parallel.

For operation execution, a module offers a module specific SOA service description. This service description specifies how to communicate with the module and how any form of production data has to be mint and formatted. The last part of the CIMory contains the above mentioned stored meta-configuration for configuring a control system instance.

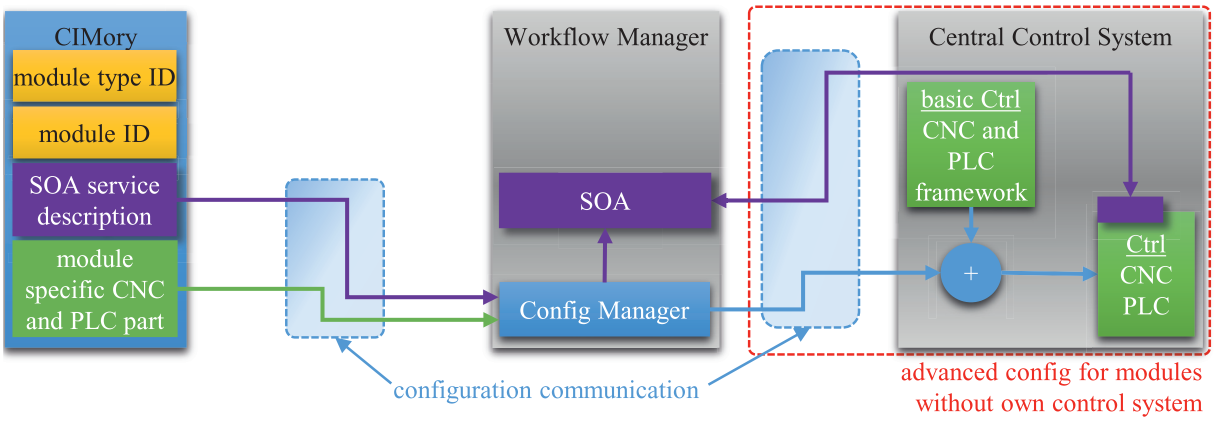

Fig. 3. Schematic overview over the content of the CIMory and the information flow for configuring a CCS-based control system.

3.2. Module switching

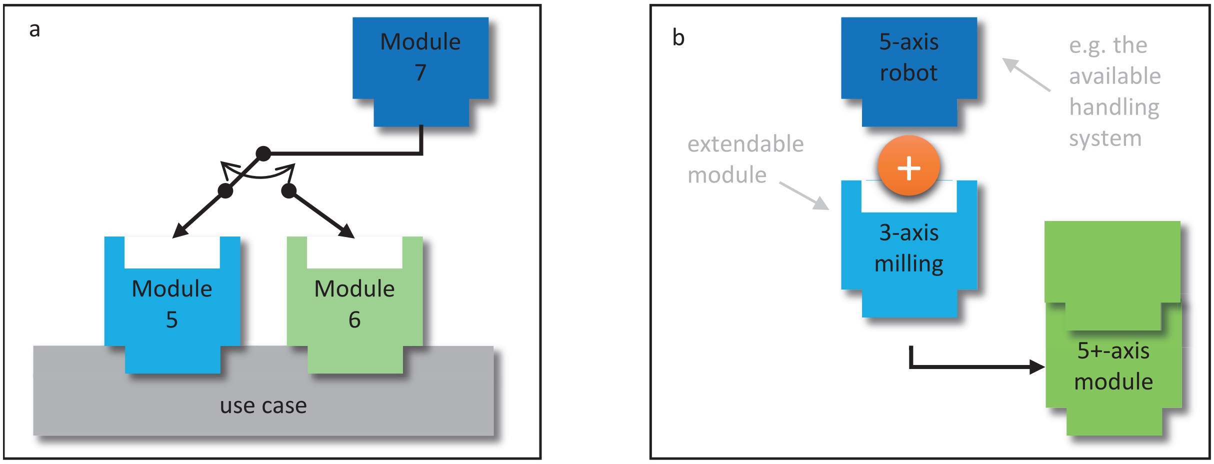

Fig. 4. (a) switching a module between modules; (b) adding a module to an extendable module.

The abstraction of the communication between the WFM and the individual modules to a service-based SOA communication makes accurate knowledge of the hardware level of the individual modules needless. Therefore, it is imaginable that modules may be linked together. This can be the case if a tool is needed that has its own intelligence e.g., an edge banding tool. The module can be attached to every module that is able to handle the extension (see Fig. 4). A merge of modules can be temporary, as shown in Fig. 4a, to execute a task a module alone cannot handle. The merge can also be permanent to expand the ability of a module e.g., the adding of a 2-axis rotary tilt table to a 3-axis milling module. Also, the use of temporarily not used modules like a handling robot can extend a 3-axis milling module by adding 2 more axes for 5-axis milling (see Fig. 4b).

For the maximum possible working time of the MPS, the reconfiguration should only lead to short idle times. Therefore, an online reconfiguration of the control level and the reallocation of the underlying field bus is needed. In case of reconfiguration, merged modules appear as a new control system to the WFM that offers new SOA services. The old control systems and their SOA services are temporarily disabled until the modules are separated again. By doing so, incorrect operation is avoided (see Fig. 5).

At the control level, the reconfiguration and the instantiation of a new control system is needed. The required configuration for CNC and PLC, as well as the new SOA service definition, for instance, is built up out of the module specific CIMory meta-configuration by the Config Manager of the WFM.

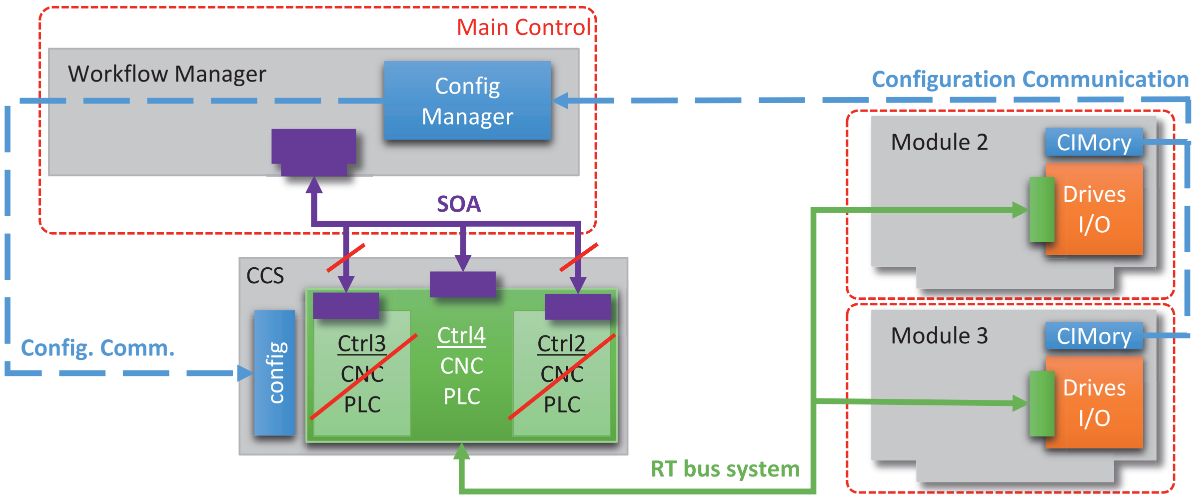

Fig 5. Changes to the system made by merging two modules together.

At the hardware level, a common real-time bus system is required to synchronize the structurally separated I/O and Drives of the merged modules. This is necessary since only a deterministic communication between the control system and the Drives and I/O enables a productive and safe execution of the entire MPS. Because of the fact, that a synchronized real-time communication with the whole I/O and Drives level is required, a merge of different combinable modules is only possible, if the hardware level works on the same real-time bus system, regardless of whether the main module has its own control system and the expanding module is subordinated, or both modules are controlled via a CCS instance of a control system.

4. Conclusion and Outlook

This paper presents a new approach for an architecture of a control system for a modular production system (MPS). The control system reconfigures itself automatically if process modules have changed. The control system follows a hierarchical structure with a Workflow Manager (WFM) as master and the controls of each process module as slaves. The communication between the modules is SOA based.

To enable the automated reconfiguration each module is equipped with a Configuration and Information Memory (CIMory) containing all necessary information. To reconfigure the system the WFM reads the information from all available modules. Each module provides a service description of all its services. Based on these descriptions the WMF is reconfigured automatically.

The system supports modules with either a highly sophisticated control with internal intelligence or with a simple command executing I/O unit. If there is no control integrated in the module the WFM initiates a new virtual, software-based control in the central control system (CCS) for the module. The module specific control information is also provided by the CIMory.

Currently this architecture is implemented on a real-time control system with distributed controls and computers in one network. In future research it has to be investigated how it can be implemented in a cloud-computing environment. Since the CCS module is designed to host multiple software-based real-time systems, it requires high computing power which can be provided by implementing the CCS in a cloud-based environment. The only requirement for a cloud-based CCS is compliance with the real-time bus system communication specifications being used by the MPS. In case of CCS-controlled modules, the module's real-time bus system is extended over its boundaries to also include the CCS (see Fig. 2).

Acknowledgements

The research leading to these results was done within the CassaMobile project which has received funding from the European Union Seventh Framework Program under grant agreement n° 609146.

References

[1] Piller FT, Stotko CM (Hrsg.). Mass Customization und Kundenintegration. Düsseldorf: Symposion Publishing GmbH; ISBN-10: 3936608059, 2003.
[2] Business Wissen. Mass Customization - Mit individualisierten Standardprodukten zum Erfolg. 17.04.2009, accessed 24.04.2014; http://www.business-wissen.de/artikel/mass-customization-mit-individualisierten-standardprodukten-zum-erfolg/.
[3] Reuter A, Kircher C, Verl A. Manufacturer-independent mechatronic information model for control systems. WGP; 2010.
[4] Wang W, Koren Y. Scalability planning for reconfigurable manufacturing systems. Journal of Manufacturing Systems; 2012.
[5] Promotorengruppe Kommunikation der Forschungsunion Wirtschaft, acatech (Ed.). Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0. 2013.
[6] Kircher C, Seyfarth M, Wurst K-H, Pritschow G. Self-Adapting Control Systems for RMS. Proceedings of the CIRP-sponsored 3rd International Conference on Reconfigurable Manufacturing; University of Michigan; Ann Arbor; USA; 10.-12. May; 2005.
[7] Reuter A. Definition eines mechatronischen Informationsmodells zur Modellierung von Automatisierungskomponenten und Maschinen. München: Verlag Dr. Hut; 2013.
[8] Litto M. Ist Mechatronik beherrschbar?, Intelligenter Produzieren; No.2; VDMA_Verlag; 2006.
[9] Pesch D. Baukasten für disziplinübergreifendes Projektieren. iee, 3; 2004.
[10] Verl A. REVOLUTION INDUSTRIE 4.0, FRAUNHOFER IPA. Interaktiv; 2; 2012.
[11] VDI. Cyber-Physical Systems: Chancen und Nutzen aus Sicht der Automation. 2013.
[12] acatech. Cyber-Physical Systems: Driving Force for Innovations in Mobility, Health, Energy and Production. Berlin, Heidelberg: Springer Verlag, 2012.
[13] Vogel-Heuser B, Kegel G, Bender K, Wucherer K. Global Information Architecture for Industrial Automation. atp, 1-2; 2009.
[14] Wiendahl H-P, Ahrens V. Agent-based control of self-organized production systems. CIRP Annals-Manufacturing Technology 1997;46(1): 365-368.
[15] Leitão P. Agent-based distributed manufacturing control: A state-of-the-art survey. Engineering Applications of Artificial Intelligence 2009;22(7):979-991.
[16] Schutz D et al. Highly reconfigurable production systems controlled by real-time agents. Emerging Technologies & Factory Automation (ETFA); 2011 IEEE 16th Conference on. IEEE; 2011.
[17] Tumer K, Wolpert, D. Collective intelligence and Braess' paradox. in: Aaai/iaai; 2000. p. 104-109
[18] Yeung WL. Behavioral modeling and verification of multi-agent systems for manufacturing control. Expert Systems with Applications 2011;38(11):13555-13562.
[19] Muller R et al. Modular control system for reconfigurable robot applications. Assembly and Manufacturing (ISAM); 2011 IEEE International Symposium on. IEEE; 2011.
[20] Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy AG et al. Reconfigurable manufacturing systems. CIRP Annals 1999; 48(2):6–12.
[21] Koren Y, Shpitalni M. Design of reconfigurable manufacturing systems. Journal of Manufacturing Systems 2010;29(4):130-141.
[22] Järvenpää E, Heikkilä R, Tuokko R. TUT-microfactory – a small-size, modular and sustainable production system. GCSM; 2013.
[23] Hoffmeister H-W, Gerdes A, Verl A, Wurst K-H, Heinze T, Batke C. Investigations of a small Machine Tool with CFRP-frame. euspen 13th International Conference; Berlin; Germany; ISBN 978-0-9566790-2-4; 2013. p. 200-203
[24] CassaMobile project, funded by the European Union Seventh Framework Program under grant agreement n° 609146, www.cassamobile.eu.
[25] OASIS, Reference Architecture Foundation for Service Oriented Architecture Version 1.0, 2012.